

STREAM TEMPERATURE RELATIONSHIPS TO FOREST  
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**ABSTRACT:** We compared summer stream temperature patterns in 40 small forested watersheds in the Hoh and Clearwater basins in the western Olympic Peninsula, Washington, to examine correlations between previous riparian and basin-wide timber harvest activity and stream temperatures. Seven watersheds were unharvested, while the remaining 33 had between 25% and 100% of the total basin harvested, mostly within the last 40 years. Mean daily maximum temperatures were significantly different between the harvested and unharvested basins, averaging 14.5°C and 12.1°C, respectively. Diurnal fluctuations between harvested and unharvested basins were also significantly different, averaging 1.7°C and 0.9°C, respectively. Total basin harvest was correlated with average daily maximum temperature ( $r^2 = 0.39$ ), as was total riparian harvest ( $r^2 = 0.32$ ). The amount of recently clear-cut riparian forest (<20 year) within 600 m upstream of our monitoring sites ranged from 0% to 100% and was not correlated to increased stream temperatures. We used Akaike's Information Criteria (AIC) analysis to assess whether other physical variables could explain some of the observed variation in stream temperature. We found that variables related to elevation, slope, aspect, and geology explain between 5% and 14% more of the variability relative to the variability explained by percent of basin harvested (BasHarv), and that the BasHarv was consistently a better predictor than the amount of riparian forest harvested. While the BasHarv is in all of the models that perform well, the AIC analysis shows that there are many models with two variables that perform about the same and therefore it would be difficult to choose one as the best model. We conclude that adding additional variables to the model does not change the basic findings that there is a relatively strong relationship between maximum daily stream temperatures and the total amount of harvest in a basin, and strong, but slightly weaker relationship between maximum daily stream temperatures and the total riparian harvest in a basin. Seventeen of the 40 streams exceeded the Washington State Department of Ecology's (DOE) temperature criterion for waters defined as "core salmon and trout habitat" (class AA waters). The DOE temperature criterion for class AA waters is any seven-day average of daily maximum temperatures in excess of 16°C. The probability of a stream exceeding the water quality standard increased with timber harvest activity. All unharvested sites and five of six sites that had 25-50% harvest met DOE's water quality standard. In contrast, only nine of eighteen sites with 50-75% harvest and two of nine sites with >75% harvest met DOE's water quality standard. Many streams with extensive canopy closure, as estimated by the age of riparian trees, still had higher temperatures and greater diurnal fluctuations than the unharvested basins. This suggests that the impact of past forest harvest activities on stream temperatures cannot be entirely mitigated through the reestablishment of riparian buffers.

(KEY TERMS: riparian ecology; fluvial processes; streamflow; land use/land cover change; temperature; watershed management.)

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## INTRODUCTION

Stream temperature affects many biological and physical processes. Temperature directly affects rates of metabolism, growth, behavior, interspecific competition, susceptibility to disease, and mortality of in-stream organisms (Coutant, 1999), and also affects physical parameters such as soluble gas concentrations (Beitinger and Fitzpatrick, 1979; Beschta et al., 1987). Temperature impacts multiple trophic levels, including periphyton, benthic invertebrates, and fishes (Markarian, 1980; Holtby, 1988; Phinney and McIntire, 2005). In the Pacific Northwest, of particular concern is the affect stream temperature has on salmonids and other cold water fishes. Increases in stream temperature have been linked to increased salmonid mortality, increased disease, and decreased competitive abilities (Brett, 1952; Coutant, 1999).

There is high spatial variation in temperature both within and between streams, some of which has been linked to anthropogenic factors. Important factors affecting stream temperature include air temperature, stream morphology, ground-water influences, and riparian and basin forest condition (Beschta et al., 1987; Broszofski et al., 1997; Poole and Berman, 2001). In the Pacific Northwest, there is conflicting information regarding the extent of riparian and upland forest needed to maintain natural stream temperature regimes, and more generally between the relative importance of factors contributing to stream temperature increases.

Regarding the importance of forest cover on stream temperature, there are three general hypotheses: (1) the condition of the riparian forest immediately upstream of a site primarily controls stream temperature, (2) the condition of the entire riparian forest network affects stream temperature, and (3) the forest condition of the entire basin affects stream temperature.

The first hypothesis, that the condition of the riparian forest immediately upstream of a site primarily controls stream temperature, derives from early observations that removal of riparian forests caused dramatic increases in stream temperatures immediately downstream (Brown, 1970; Brown and Krygier, 1970; Brazier and Brown, 1973). Others observed that increased stream temperature was correlated with increased air temperatures (Adams and Sullivan, 1990; Sullivan et al., 1990; Larson and

Larson, 1997). Sullivan et al. (1990) hypothesized that streams sought a dynamic equilibrium with the surrounding environment, such that thermal energy inputs and outputs were approximately equal. Therefore, they hypothesized that air temperature strongly influenced stream temperatures because streams were constantly seeking thermal equilibrium with the surrounding air. Decreases in stream temperature under shade were assumed to be the result of convective heat exchanges (Larson et al., 2002). Therefore, streams heated due to a lack of riparian canopy should rapidly drop in temperature after passing through a shaded reach with cooler air temperatures (Sullivan et al., 1990; Zwieniecki and Newton, 1999). For forests in western Washington, Sullivan et al. (1990) estimated that 600 m of riparian canopy would ameliorate stream temperature increases caused by a lack of riparian canopy further upstream.

The second hypothesis, that the condition of the entire upstream riparian network influences stream temperature, emerged from observations that long-term increases in stream temperature were correlated with the condition of the entire upstream riparian forest (Beschta et al., 1987; Beschta and Taylor, 1988). For example, Beschta and Taylor (1988) examined a 30-year period of record for a 325 km<sup>2</sup> stream in western Oregon and found that peaks in daily maximum temperatures at the mouth of the stream increased as the total amount of forest harvest in the basin increased. As the clear-cut forests regenerated, the daily maximum temperatures at the mouth of the watershed decreased. Similarly, Barton and Taylor (1985) found that the maximum weekly temperatures in southern Ontario streams were most strongly correlated with the total upstream length of the forested riparian buffer. Scrivener and Andersen (1984) observed temperature increases in Carnation Creek, British Columbia, coincident with extensive upstream riparian forest removal, even though a riparian buffer remained for over 800 m immediately upstream of where temperature measurements were taken. Finally, Jones et al. (2006) concluded that a recent reduction in required riparian buffer widths from 30 to 15 m in streams throughout Georgia will likely cause daily maximum stream temperature increases of 1°C to 2°C.

There are several proposed mechanisms to explain why the entire upstream riparian network influences stream temperature. One is that thermal loading to

the stream caused by absence of a riparian canopy is not completely removed by convective heat exchanges when the stream re-enters a shaded section, such that canopy removal results in a downstream thermal signature or cumulative effect (Beschta et al., 1987; Bourque and Pomeroy, 2001). Another possible mechanism is that removal of upstream riparian vegetation results in bank instability, which results in wider, shallower streams, higher sediment loads, and reduced permeability of alluvial substrates (Beschta and Taylor, 1988; Dose and Roper, 1994; Bartholow, 2000). This implies that not only is the upstream thermal load increased, but that even in downstream shaded reaches, the shading is not as efficient because the stream is wider and shallower, and heating is more rapid (Poole and Berman, 2001). Further, deposition of fine sediment on coarser alluvium reduces the exchange of surface waters with cooler hyporheic and ground waters (Moring, 1982). Riparian forest removal may also indirectly increase stream temperatures by reducing woody debris recruitment, which reduces flow retention (Meehan et al., 1979; Holtby, 1988). Further, woody debris retains sediment, resulting in an increased hyporheic zone and increased exchange between surface and hyporheic waters, which helps to cool surface waters (Johnson and Jones, 2000). Thus the loss of woody debris can increase stream temperature by reducing the hyporheic volume.

The third hypothesis, that the forest condition of the entire basin affects stream temperatures, derives from observations that in some circumstances, stream temperatures increased after extensive forest harvest, even when riparian forests were protected (Hewlett and Fortson, 1982; Brosnokske et al., 1997; Bourque and Pomeroy, 2001). A proposed mechanism in these studies was that forest removal away from streams heated soils containing shallow ground-water sources that fed into the stream. Both Brosnokske et al. (1997) and Bourque and Pomeroy (2001) found stream temperature was not correlated with the width of riparian buffers. For example, in their study of five watersheds in New Brunswick, Bourque and Pomeroy (2001) found that buffers 30-60 m wide did little to reduce the temperatures of streams >0.5 m wide once they had been heated as a result of upstream and upland forest harvest. They attributed this to the heating of both the surface water of streams <0.5 m wide that were not buffered, and the heating of shallow ground-water sources that fed into the streams.

It has also been observed that the microclimate impacts of upland forest removal such as increased air temperatures, reduced relative humidity, and increased wind speed, extended hundreds of meters into adjacent forests, distances far greater than the

width of most riparian buffers (Chen et al., 1992, 1995; Brosnokske et al., 1999). Additionally, even with riparian buffers present, the quantity of light reaching streams still increases (Kiffney et al., 2004). Although much of this light is indirect, it is still sufficient to increase the biomass of instream primary producers such as periphyton, and may affect stream temperature.

Also, in mountainous watersheds, upland forest removal on unstable slopes can trigger mass soil movements that deliver large sediment loads to streams, thus widening and shallowing streams and impacting stream temperatures (Sidle, 1985; Beschta and Taylor, 1988). Finally, removing upland vegetation may increase stream temperatures by increasing surface runoff, which in turn can decrease aquifer storage and decrease ground-water inflow (Grant and Swanson, 1990; Jones and Grant, 1996; Coutant, 1999). Bartholow (2000) used a stream heating model to assess how various changes to stream and riparian conditions affected stream temperatures for conditions typical of a forested, medium-sized stream in western Washington. He found that the three biggest factors affecting stream temperature were the loss of the upstream riparian canopy (1.5°C increase), channel widening (1.4°C increase), and increased air temperature (0.6°C increase).

Taken together, these studies collectively suggest that stream heating might be due to a variety of mechanisms that are triggered both by extensive riparian and upslope timber harvest. At the same time, within our study area, there are few watersheds where most of the riparian forest was left intact while the upland forests were harvested. This is because until very recently forest practice regulations did not require riparian protection on the smaller streams, which make up the majority (>80%) of the riparian network. Thus, discerning between the effects of extensive riparian harvest and extensive basin-wide harvest may be challenging.

In this paper, we examine correlations between forest harvest patterns and summer stream temperatures for 40 western Washington streams to assess whether harvest patterns of riparian or upland forest can predict variation in temperature regimes among streams. Specifically, we ask whether the temperature regimes observed in these streams are correlated with the condition of the immediate upstream riparian forest, or more correlated with forest conditions more spatially distant and on a coarser scale, such as the entire upstream riparian forest network or the forest condition of the entire basin. We also discuss to what extent the stream temperature maxima and fluctuations observed in our study are likely to affect instream biota, particularly salmonids.

## METHODS

This study was conducted on the west side of the Olympic Peninsula, Washington, primarily on tributaries to the Clearwater (area = 393 km<sup>2</sup>) and Hoh (area = 770 km<sup>2</sup>) Rivers (Figure 1). The rivers originate in the Olympic Mountains and flow westward through glacially carved valleys, across a coastal plain composed primarily of glacial materials, and empty directly into the Pacific Ocean. Elevation ranges from sea level to 2,428 m at the peak of Mount Olympus. The low-elevation coastal climate is very wet, with cool summers and mild but cloudy winters. Annual rainfall in the area ranges from 400 to 3,500 mm, the majority of which falls as rain and snow during the months between October and March. Afternoon air temperatures during the summer months range from 18°C to 27°C, with night temperatures dropping to 7°C. Winter temperatures are cooler with afternoon temperatures around 4°C and decreasing to near freezing at night (National Park Service, unpublished data).

The bedrock geology of the region consists mostly of uplifted sedimentary rocks formed in the Miocene and Eocene, with a layer of uplifted oceanic basalt in the northern, eastern, and southern parts of the Peninsula. Much of the area was glaciated during the Pleistocene. Alpine glacial deposits are present in all the major west trending river valleys to an elevation of about 250 m and are present across most of the

coastal plains and foothills to the west. The terrain is steep and mountainous, which in combination with the high rainfall results in frequent channelized landslides (debris flows). Many debris flows are initiated where roads cross streams in steep terrain or on steep slopes where extensive clear-cut harvest has occurred, and recent timber harvest plans are designed to minimize the probability of slope failures in this debris-flow prone terrain (WDNR 1997). Land ownership on the western Peninsula is a mix of public and private owners, including the National Park Service, the United States Forest Service, the Washington Department of Natural Resources (DNR), and a number of large timber companies. Outside of Olympic National Park, most land is actively managed to produce timber.

Most of the low-lying areas are within the Sitka spruce (*Picea sitchensis*) vegetation zone (Franklin and Dyrness, 1979). Common tree species in addition to Sitka spruce include western red cedar (*Thuja pllicata*), western hemlock (*Tsuga heterophylla*), Douglas-fir (*Pseudotsuga menziesii*), big leaf maple (*Acer macrophyllum*), and red alder (*Alnus rubra*), with black cottonwood (*Populus trichocarpa*), and willow (*Salix*) common in riparian areas. The rivers and streams of this region provide important habitat for several species of salmonids. These include summer and winter steelhead (*Oncorhynchus mykiss*); spring, summer, and fall chinook (*O. tshawytscha*); chum (*O. keta*); coho (*O. kisutch*); pink (*O. gorbuscha*) and sockeye (*O. nerka*) salmon; resident/sea-run cutthroat

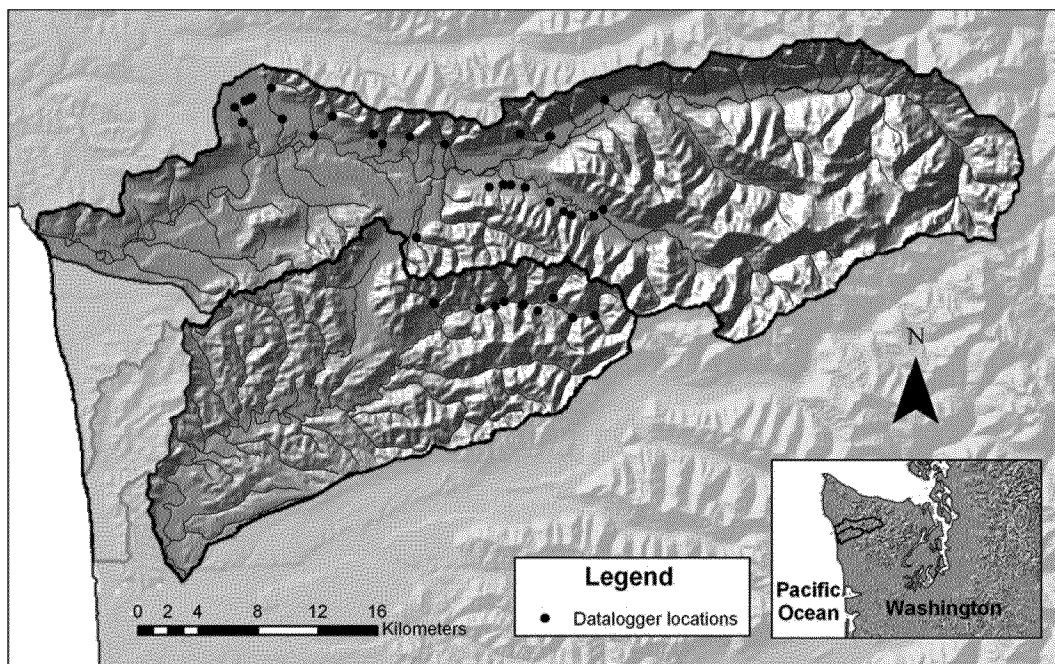


FIGURE 1. Site Map Showing Tributaries in the Hoh and Clearwater Basins Where Temperatures Were Monitored.

trout (*O. clarki*); and Dolly Varden char (*Salvelinus malma*) (Smith, 2003). Common stream-dependent amphibians in the study area include tailed frogs (*Ascaphus truei*); Olympic torrent salamanders (*Rhyacotriton olympicus*); and Cope's giant salamander (*Dicamptodon copei*).

### Site Selection

We selected 42 subbasins on DNR lands for temperature monitoring. Twenty-two subbasins were located on tributaries to the main stem Hoh River, ten sites in the South Fork Hoh River basin, nine in the Clearwater River basin, and one on a small tributary to the Bogachiel River, just outside the Hoh basin (Figure 1). Sites were selected to represent mountainous conditions typical of perennial tributaries to the Clearwater and Hoh River basins. Because we were interested primarily in effects of timber harvest patterns on stream temperatures, sites were constrained to a relatively narrow range of subbasin sizes (approximately 1-10 km<sup>2</sup>) and elevation (75-400 m). To minimize the potential confounding effects of different geologies, we focused this study on mountainous tributary subbasins underlain by sedimentary rock that were known to have perennial flow. Within this general geology type we looked at a range of forest harvest conditions. Site selection was generally limited to streams that could be reasonably accessed from a road.

### Data Collection and Analysis

Stowaway Tidbit submersible data loggers (Onset Computer Corporation, Pocasset, Massachusetts) were programmed to store temperature readings every 15 minutes and placed in 42 streams beginning July 1, 2004 and ending August 31, 2004 for a total of 62 days. The accuracy of the Tidbit data loggers is  $\pm 0.2^{\circ}\text{C}$ . Data loggers were placed in protective coverings of either hard plastic mesh or perforated PVC pipe, weighted, and placed in a pool with good flow. They were then tied with rope to a stationary object such as a root, overhanging tree, or large rock and flagged for reference. When near a road, they were placed upstream of the road crossing. Only data loggers remaining in the stream for the entire time period were used for analyses. Data from two of the data loggers could not be used because they were not submerged at low flows. Thus, data from 40 of the loggers were available for analyses. We calculated temperature summary statistics for each site [average daily maximum (ADM), average daily range, seasonal range, average, maximum, and minimum] (Table 1). The ADM for a stream is the maximum

temperature from each day averaged over the 62 days that the temperature loggers were in the streams. The average daily range for a stream is the difference between the maximum and minimum temperature from each day averaged over the 62 days that the temperature loggers were in the streams.

The DNR maintains a detailed geographic information systems (GIS) coverage of its forest inventory showing the exact location of each harvest unit and the year of harvest. We used the 2002 inventory and thus the term "before present" (bp) refers to before 2002. Because the DNR has to set timber harvest boundaries, ensure compliance with stream buffer regulations, and to maintain a constant assessment of the value of their timber base, the forest inventory data layer is very accurate. Timber harvest boundaries and any associated riparian buffers are first identified by the DNR using aerial photographs, then precisely delineated and mapped on the ground with field crews. Aerial photographs are again obtained after timber harvest activities and those are used to delineate the final stream, buffer, and timber harvest boundaries. Further, we did some field verification of riparian forests. In particular we wanted to ensure that riparian forests mapped as unharvested were in fact unharvested. All riparian forests we examined were consistent with the forest inventory data layer. Most of the study area was unharvested until the 1960s when construction began in earnest on an extensive road network in order to gain access to the valuable old-growth timber in this (formerly) remote region. Therefore almost all of the harvested timber stands are less than 40-year old.

Using this forest inventory coverage, we defined the "near upstream riparian forest" as a band 30 m wide on each side of the stream and extending 0-600 m upstream of the data loggers. For forests in western Washington, Sullivan et al. (1990) estimated that 600 m of riparian canopy would ameliorate stream temperature increases caused by a lack of riparian canopy further upstream, so we did not extend our analysis beyond 600 m upstream of our sites for our "near upstream riparian forest" classification.

The "riparian forest network" was defined as a 30 m wide band on each side of all channels identified in the DNR hydrology layer that were upstream of the temperature loggers. The hydrography layer was originally delineated by DNR field crews who used geographic positioning systems (GPS) to map the upstream end of all channels. The upstream end of the channel was defined as the point where there was no longer evidence of sediment transport within definable banks. The DNR then used aerial photography combined with digital elevation model (DEM) flow-path modeling to verify the GPS derived channel and channel head locations prior to any logging in a

TABLE 1. Basin Characteristics and Stream Temperature Characteristics for the 40 Streams Monitored in This Study.

Stream	ID Number	Elevation (m)	Slope	Aspect	Basin Area (km <sup>2</sup> )	Channel Width (m)	Basin Harvested (%)	Riparian Network Harvested (%)	Upstream Buffer <20-year Old (%)	ADMX (°C)	ADR (°C)	Avg (°C)	Min (°C)	Max (°C)	Range (°C)
West Twin	1	252	0.16	SE	0.4	1.8	0	0	0	9.6	0.9	9	8	12.6	4.6
Spruce	12	229	0.09	SE	2.5	3.8	43	52	61	10.9	0.4	10.7	9.5	12.3	2.8
Taft	5	183	0.09	SE	1.9	3.3	0	0	0	11	0.7	10.6	9.1	12.4	3.3
Devils Club	2	155	0.04	SW	0.7	2.1	0	0	0	11.4	0.9	10.9	9.5	13.7	4.2
Boundary	16	221	0.06	NW	3	4	54	35	0	12.4	1	11.7	9.8	14	4.2
Noisy	20	370	0.08	NE	3.5	4.3	64	68	17	12.7	1.2	11.9	9.2	14.5	5.3
East Twin	3	148	0.01	S	0.7	2.1	0	0	0	12.8	1.3	12	10.1	14.4	4.3
Big Flat	4	236	0.14	SW	1.3	2.8	0	0	0	13.1	0.8	12.7	10.3	14.9	4.5
Fish	9	173	0.1	N	1	2.5	29	30	0	13.1	1.4	12.4	10.1	15.1	5
Rock	11	220	0.06	SW	1.3	2.8	38	38	0	13.1	0.9	12.6	10.2	15	4.8
Lidner	6	150	0.1	SW	2.4	3.7	2	0	0	13.2	0.6	12.9	10.8	14.4	3.6
Elk	18	206	0.19	NE	1.1	2.6	56	2	0	13.3	2	12	9.7	15.9	6.2
Line	24	236	0.11	NE	2.6	3.8	69	58	2	13.3	1.1	12.7	10.3	15.4	5.1
King	36	243	0.25	S	2.9	4	92	92	35	13.3	0.9	12.8	10.3	14.7	4.5
Willoughby Tributary	19	183	0.1	SW	4.4	4.8	59	58	0	13.6	1.1	13	10.8	15.5	4.7
Clearwater	15	400	0.1	W	7.5	6	54	64	88	13.7	1.5	12.8	9.7	15.6	5.9
Tower	7	231	0.12	SW	2.6	3.8	9	12	6	13.9	0.9	13.3	11	15.9	4.8
Fly	35	346	0.09	NW	2.4	3.7	88	91	88	14	1.5	13.2	10	15.9	5.9
WF Kunamakst	17	284	0.06	SE	6	5.4	55	59	18	14.1	1.3	13.4	10.8	16.4	5.6
Alder Tributary	25	118	0.02	SE	5.2	5.1	70	71	31	14.2	1.6	13.3	10.7	16.3	5.6
EF Kunamakst	13	267	0.08	SW	2.1	3.4	47	55	100	14.3	1.6	13.4	10.4	16.5	6.1
Alder	26	193	0.04	SW	3.7	4.4	71	68	21	14.4	2	13.2	10.7	16.9	6.2
EF Hell Roaring	39	151	0.02	SW	0.3	1.5	100	100	0	14.4	1.2	13.7	11.2	16.1	4.8
Hell Roaring Tributary	10	140	0.03	SE	0.7	2.2	30	55	71	14.5	1.3	13.8	11.4	16.7	5.3
Cedar	22	234	0.21	NW	2.6	3.8	65	64	0	14.5	1.5	13.6	10.5	16.9	6.4
NF Clearwater	30	363	0.05	SW	5.4	5.2	73	78	88	14.5	2	13.4	10.1	16.8	6.7
Maple	28	204	0.01	NE	8.3	6.3	72	77	11	14.6	1.8	13.6	10.9	17	6.1
Falls Cr Mouth	34	298	0.33	N	2	3.4	79	0	22	14.6	2	13.6	9.8	17.1	7.3
Willoughby	27	88	0.04	SE	8.2	6.2	72	69	0	15	1.9	13.9	11.2	17.3	6.1
Washout	29	190	0.12	NW	0.4	1.8	72	78	0	15	1.2	14.3	11.5	17.4	6
WF Hell Roaring	8	151	0	SE	1	2.5	26	27	0	15.1	1.1	14.4	11.9	17.7	5.8
Split	32	184	0.2	NE	1.9	3.3	76	66	20	15.5	2.3	14.3	10.5	18.8	8.3
Suzy	23	275	0.05	S	4.2	4.7	67	59	44	15.7	3	13.9	10.1	18.4	8.3
Hell Roaring	14	119	0.03	SE	10.1	6.8	53	53	5	15.8	1.7	14.7	12	19	7
Wilson	38	229	0.2	S	4.4	4.8	99	97	1	16	2.1	14.6	11.3	18.8	7.5
May	37	76	0.04	NE	5.4	5.2	98	100	18	16.1	1.8	15	12	19	7.1
Iron Maiden	33	230	0.02	N	0.6	2	78	86	11	16.6	3.8	14	10.6	20.5	10
Beaver	40	151	0.01	SW	0.7	2.1	100	100	0	16.7	3.5	14.9	10.7	19.8	9.1
Deer	21	154	0.02	SW	3.6	4.4	64	66	0	17.1	2.1	16	12.7	20	7.3
Virginia Falls	31	186	0.13	NE	2	3.4	74	62	2	17.4	3.2	15.6	11.4	21.6	10.2

Notes: ADMX, average daily maximum; ADR, average daily range.

Basins are sorted in ascending order of average daily maximum temperatures.

timber harvest unit, the location of streams and stream buffers are field verified by DNR personnel.

The “total basin forest area” was defined as the entire area of the basin. We created the basin perimeters manually in GIS, using the hydrography layer to initially set boundaries, and then visually inspecting the data layer and adjusting the boundaries relative to the 30 m DEMs. All basins had 100% of their land base in commercial forest or else were in Olympic National Park and contained 100% unharvested forest cover. Forest condition was initially classified as recently clear-cut (harvested <20 year bp), young 20-40 year bp, mature 40-150 year bp, or old >150 year bp (unharvested). The category of “recently clear-cut” was used as an index of the extent that canopy was insufficient to protect streams from direct solar radiation (based on Summers, 1983).

Using linear regression, we correlated daily stream temperature maxima and ranges with the percentage of forest recently clear-cut (<20-year old) and the percentage of total forest harvested (mostly <40-year old) in (1) the near upstream riparian forest, (2) the riparian forest network, and (3) the entire subbasin. We also implemented a more comprehensive statistical analysis based on model selection and

information theory using Akaike's Information Criteria (AIC) (Burnham and Anderson, 1998) to assess whether other factors such as elevation, basin area, aspect, slope, or geologic composition of the basin could be significant correlates with stream temperature.

## RESULTS

### Distribution of Forest Ages

The distribution of age classes for all the sites is illustrated in Figure 2. Basin forest age distributions ranged from 100% unharvested to 100% harvested within the past 40 years. Two dominant age classes exist in all of the sites, forests <40-year old, and unharvested forest >150-year old. For the 33 subbasins where some harvest occurred, the average proportion of forest between the ages of 40-150 was just 0.019. For the 33 harvested subbasins taken as a whole, roughly 1/3 of the subbasin forests were <20 years, 1/3 between 20-year and 40-year old, and 1/3 unharvested.

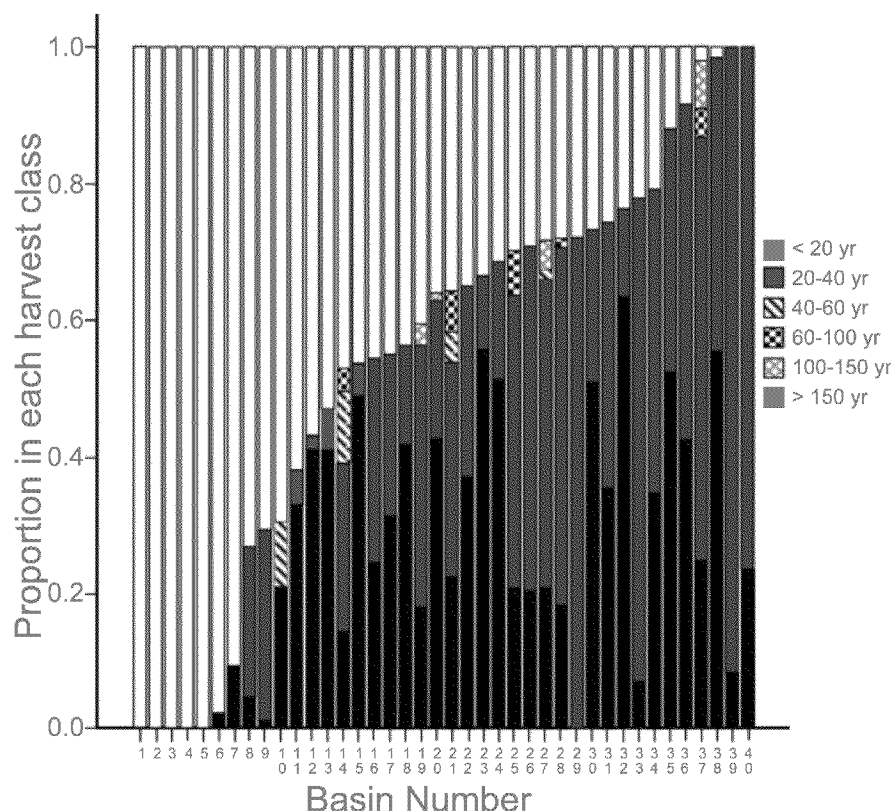


FIGURE 2. Age Class Distribution of Forest by Basin, Demonstrating That Only Two Major Age Classes Exist for Most Basins, <40 and >150 Years. Basin numbers correspond to ID Number in Table 1.

## General Temperature Patterns

Average daily maximum temperatures ranged from 9.6°C to 17.4°C. Seasonal maximum temperatures ranged from 12.3°C to 21.6°C, while seasonal minimum temperatures ranged from 8°C to 12.7°C. Average temperatures ranged from 9°C to 16°C, while average daily ranges (ADR) ranged from 0.4°C to 3.1°C. ADM temperatures were strongly correlated with average diurnal fluctuations ( $r^2 = 0.87$ ,  $p < 0.001$ ,  $n = 40$ ), indicating that cool streams also had more stable temperatures. The contrast in temperature regimes between warm and cool streams can be seen in Figure 3, which shows the daily maximums and minimums for Taft Creek, a cool stream with stable temperatures, and Virginia Falls Creek, a warm stream with high diel fluctuations. The two basins are physically similar in terms of basin area, and the elevation, slope, and channel width where the stream temperature data were collected, excepting that Taft is a southeast-facing watershed and Virginia Falls is a northeast-facing watershed (see Table 1). Virginia Falls Creek has been extensively harvested and runs warm and has high diel fluctuations. In contrast, no harvest has occurred in the Taft Creek basin and temperatures are cool with little fluctuation.

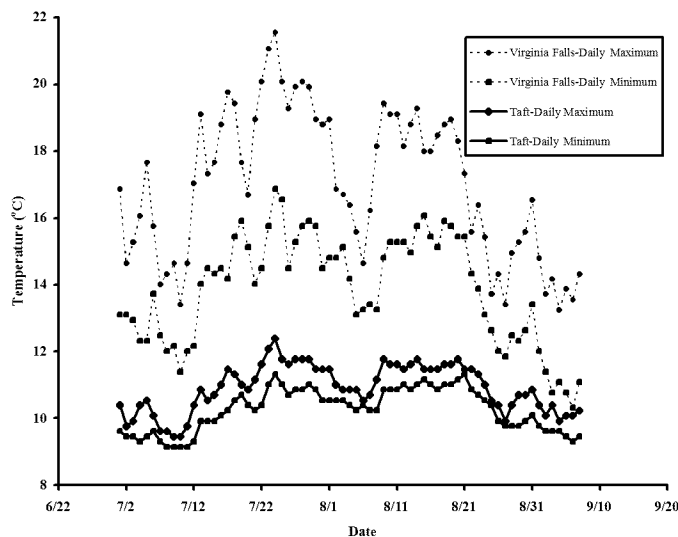


FIGURE 3. Comparison of Maximum and Minimum Daily Temperatures Between the South-Facing Taft Creek, an Unlogged Watershed, and the North-Facing Virginia Falls Creek, a Watershed That Has Had 74% of Its Forest Harvested in the Last 40 Years and Experienced Several Debris Flows in the Past 20 Years. The two basins are physically similar in terms of basin area, and the elevation, slope, and channel width where the stream temperature data were collected (see Table 1). The temperature regime in Taft Creek is typical of streams in unharvested basins, with cool, stable temperatures throughout the summer.

## Basin-Level Harvest and Temperature

The proportion of total basin harvest (Bas Harv) averaged 0.55 ( $SD \pm 0.31$ ) and ranged from 0.0 to 1.0 (Table 1). The percentage of the basin harvested explained 39% of the variation in the ADM among subbasins ( $r^2 = 0.39$ ,  $p < 0.001$ ,  $n = 40$ , Figure 4a) and 32% of variation in the ADR ( $r^2 = 0.32$ ,  $p < 0.001$ ,  $n = 40$ ). The percent harvest of the basin was also correlated with other temperature parameters such as the average temperature, the seasonal maximum, and seasonal temperature range ( $r^2 = 0.34$ , 0.35, 0.34, respectively, all  $p < 0.001$ ,  $n = 40$ ). The total percentage of subbasin forest harvested within the last 20 years was not significantly correlated to ADM or ADR.

Comparisons of temperature regimes between the seven unharvested subbasins with the 33 remaining subbasins (with harvest levels between 25% and 100%) demonstrate that streams in unharvested basins have cooler temperatures that fluctuate less. The median ADM for the unharvested subbasins was 12.8°C (average = 12.1°C), which was significantly lower than 14.5°C, the median (and average) ADM for the harvested subbasins ( $p < 0.001$ , Kolmogorov-Smirnov two sample test). Likewise, the median (and average) ADR for the unharvested subbasins was 0.9°C, which was significantly lower than 1.6°C, the median ADR (average = 1.7°C) for the harvested subbasins ( $p < 0.001$ , Kolmogorov-Smirnov two sample test).

## Riparian Network Forest Harvest and Temperature

The proportion of total riparian harvest averaged 0.52 ( $SE \pm 0.05$ ) and ranged from 0.0 to 1.0 (Table 1). The total percentage of the riparian forest network upstream of temperature loggers harvested explained 33% of the variation in the ADM among subbasins ( $r^2 = 0.33$ ,  $p < 0.001$ ,  $n = 40$ , Figure 4b) and 20% of variation in the ADR ( $r^2 = 0.20$ ,  $p = 0.003$ ,  $n = 40$ ). The percent harvest of the upstream riparian forest was also correlated with other temperature parameters such as the average temperature, the seasonal maximum and seasonal temperature range ( $r^2 = 0.31$ , 0.28, and 0.20, respectively, all  $p < 0.001$ ,  $n = 40$ ). The total percentage of upstream riparian forest harvested within the last 20 years was not significantly correlated to ADM or ADR. Relations between total upstream riparian harvest patterns and stream temperatures were very similar to those observed between basin-level harvest patterns and stream temperature, but basin harvest was a better predictor of stream

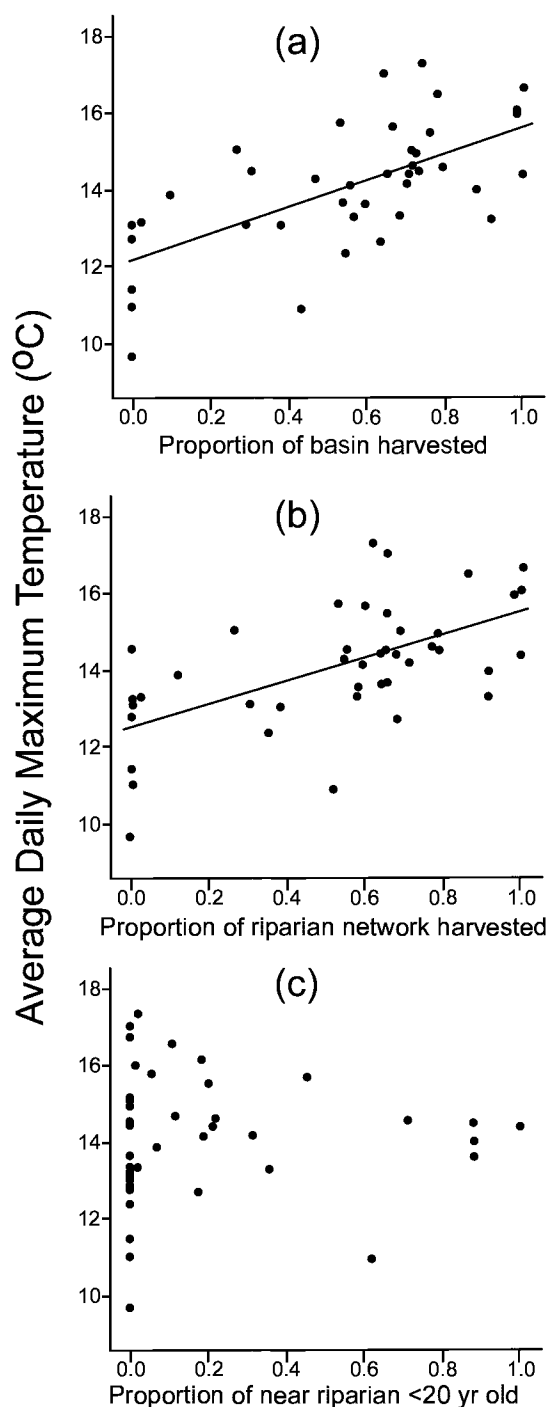


FIGURE 4. Correlations Between (a) the Amount of Basin Harvest and Average Daily Maximum Temperature ( $r^2 = 0.39$ ,  $p < 0.001$ ,  $n = 40$ ), (b) the Amount of Riparian Network Harvest and Average Daily Maximum Temperature ( $r^2 = 0.32$ ,  $p < 0.001$ ,  $n = 40$ ), and (c) the Amount of Riparian Buffer Within 600 m Upstream of a Site <20-Year Old and Average Daily Maximum Temperature ( $r^2 = 0.03$ ,  $p = 0.78$ ,  $n = 40$ ).

temperature. There was a strong correlation between total upstream riparian harvest and total basin harvest (Pearson correlation = 0.87,  $p < 0.001$ ,

$n = 40$ ). This is not unexpected, because most of the harvest in our study area occurred at a time when there was little riparian protection, especially for smaller streams.

#### Near Upstream Riparian Harvest and Temperature

The proportion of near upstream riparian buffer recently clear-cut (<20 year) averaged 0.23 ( $SE \pm 0.05$ ) across all basins and ranged from 0.0 to 1.0 (Table 1). We did not find any significant correlations between the percentage of near upstream riparian forest recently clear-cut and ADM temperature ( $r^2 = 0.03$ ,  $p = 0.79$ ,  $n = 40$ , Figure 4c), the ADR of stream temperatures ( $r^2 = 0.02$ ,  $p = 0.61$ ,  $n = 40$ ) or any other stream temperature parameters. The proportion of total harvested near upstream riparian forest (avg = 0.66,  $SD \pm 0.34$ , range = 0.0-1.0) was weakly correlated with ADM ( $r^2 = 0.12$ ,  $p = 0.02$ ,  $n = 40$ ) and not significantly correlated with ADR ( $r^2 = 0.07$ ,  $p = 0.06$ ,  $n = 40$ ). We also shortened the upstream riparian corridor length to 400 m and then to 200 m, and narrowed the definition of recently harvested to <10 year, but could not find any significant relationships between temperature and the condition of the near upstream riparian forest.

#### Physical Landscape Variables and Temperature

We used AIC analysis to assess whether physical variables other than forest harvest could explain some of the observed variation in ADM stream temperatures. Those results are presented in Table 2. We found that the variables of elevation, slope, aspect, percent of the basin with a glacial surficial geology, upstream distance of the site to sedimentary (bedrock) geology, and the percent of sedimentary surficial geology in the basin individually explain between 5% and 14% more of the variability relative to BasHarv. Adding any one of these variables to the model increases the  $R^2$  from 0.40 up to between 0.48 and 0.51. The best model included BasHarv and the square root of the amount of surficial geology that is glacial in origin (sqrtGlac) as predictor variables. The results of the AIC analysis show that there are many models with two variables that perform about the same and therefore it would be difficult to choose one as the “best” model. However, BasHarv is in all of the models that perform well. In fact, no model without BasHarv performed better than the model with BasHarv as a single independent variable. The best model without BasHarv (model #32) has a delta AIC of 7.0 suggesting it has

TABLE 2. AIC Parameters for the Top 50 Models Using All Combinations of Independent Variables to Estimate Average Daily Maximum Temperature.

Model Number	Model	Parameters	Log-Likelihood	AICc	Delta AICc	AICc Weight	R Squared
1	BasHarv, sqrtGlac	2	62.9	134.7	0.0	0.1	0.51
2	BasHarv, logArea, sqrtGlac	3	62.1	135.6	0.9	0.1	0.53
3	BasHarv, Sed	2	63.5	135.9	1.3	0.1	0.50
4	BasHarv, logSlope	2	63.7	136.3	1.6	0.1	0.49
5	BasHarv, Elevm, logSlope	3	62.6	136.7	2.0	0.0	0.52
6	BasHarv, logSlope, sqrtGlac	3	62.6	136.7	2.0	0.0	0.52
7	BasHarv, logArea, Sed	3	62.8	136.9	2.3	0.0	0.51
8	BasHarv, Elevm, sqrtGlac	3	62.8	137.0	2.3	0.0	0.51
9	BasHarv, Sed, sqrtGlac	3	62.8	137.0	2.3	0.0	0.51
10	BasHarv, Bedrockdist	2	64.1	137.1	2.4	0.0	0.48
11	BasHarv, aRad, sqrtGlac	3	62.9	137.1	2.5	0.0	0.51
12	BasHarv, sqrtGlac, RipN_harv	3	62.9	137.2	2.5	0.0	0.51
13	BasHarv, sqrtGlac, Bedrockdist	3	62.9	137.2	2.5	0.0	0.51
14	BasHarv, Elevm	2	64.2	137.3	2.6	0.0	0.48
15	BasHarv, logSlope, Sed	3	63.0	137.5	2.8	0.0	0.51
16	BasHarv, Elevm, Sed	3	63.1	137.5	2.9	0.0	0.51
17	BasHarv, logSlope, Bedrockdist	3	63.3	138.1	3.4	0.0	0.50
18	BasHarv, Elevm, Bedrockdist	3	63.4	138.2	3.5	0.0	0.50
19	BasHarv, logSlope, logArea	3	63.4	138.3	3.6	0.0	0.50
20	BasHarv, aRad, Sed	3	63.5	138.3	3.6	0.0	0.50
21	BasHarv, Sed, Bedrockdist	3	63.5	138.4	3.7	0.0	0.50
22	BasHarv, Sed, RipN_harv	3	63.5	138.4	3.8	0.0	0.50
23	BasHarv, logSlope, aRad	3	63.6	138.6	4.0	0.0	0.49
24	BasHarv, logSlope, RipN_harv	3	63.6	138.7	4.0	0.0	0.49
25	BasHarv, logArea, Bedrockdist	3	63.9	139.1	4.5	0.0	0.49
26	BasHarv, Elevm, logArea	3	63.9	139.3	4.6	0.0	0.49
27	BasHarv, aRad, Bedrockdist	3	64.0	139.4	4.7	0.0	0.48
28	BasHarv, Elevm, RipN_harv	3	64.0	139.5	4.8	0.0	0.48
29	BasHarv, Bedrockdist, RipN_harv	3	64.1	139.6	4.9	0.0	0.48
30	BasHarv, Elevm, aRad	3	64.2	139.8	5.1	0.0	0.48
31	BasHarv	1	66.8	140.2	5.5	0.0	0.40
32	sqrtGlac, RipN_harv	2	66.4	141.7	7.0	0.0	0.42
33	Sed, RipN_harv	2	66.5	141.8	7.1	0.0	0.42
34	BasHarv, RipN_harv	2	66.6	142.1	7.4	0.0	0.41
35	Elevm, RipN_harv	2	66.7	142.3	7.6	0.0	0.41
36	aRad, Sed, RipN_harv	3	65.5	142.4	7.8	0.0	0.44
37	BasHarv, logArea	2	66.8	142.5	7.8	0.0	0.41
38	BasHarv, aRad	2	66.8	142.5	7.8	0.0	0.41
39	aRad, sqrtGlac, RipN_harv	3	65.6	142.6	7.9	0.0	0.44
40	logArea, sqrtGlac, RipN_harv	3	65.7	142.7	8.0	0.0	0.44
41	logArea, Sed, RipN_harv	3	65.7	142.8	8.1	0.0	0.44
42	Bedrockdist, RipN_harv	2	67.0	142.8	8.2	0.0	0.40
43	aRad, Bedrockdist, RipN_harv	3	65.8	143.1	8.4	0.0	0.43
44	Elevm, aRad, RipN_harv	3	66.0	143.4	8.7	0.0	0.43
45	RipN_harv	1	68.5	143.6	8.9	0.0	0.35
46	Elevm, Sed, RipN_harv	3	66.1	143.6	8.9	0.0	0.43
47	logSlope, RipN_harv	2	67.4	143.7	9.1	0.0	0.39
48	Elevm, sqrtGlac, RipN_harv	3	66.2	143.8	9.1	0.0	0.42
49	Elevm, logArea, RipN_harv	3	66.4	144.1	9.5	0.0	0.42
50	Elevm, Bedrockdist, RipN_harv	3	66.4	144.2	9.5	0.0	0.42

Notes: AIC, Akaike's Information Criteria; aRad, aspect, in radians; BasHarv, percent of basin harvested; bedrockdist, distance upstream from site to bedrock; Elevm, elevation of data logger location, in meters; glac, percent of basin covered by glacial material; logSlope, slope of the stream at data logger location; RipN\_harv, percent of upstream riparian network harvested; sed, percent of basin covered by sedimentary rock (bedrock).

moderately low support relative to the best models. Also, in all of the best two-variable models (i.e., BasHarv + physical habitat variable), the coefficient for BasHarv and its' SE stay essentially the same

(about 3.4 with SE about 0.64). Therefore, we conclude that adding additional variables to the model does not change the basic finding that there is a relatively strong relationship between ADM stream

temperatures and the total amount of harvest in a basin.

Models that included the total amount of upstream riparian network harvest (RipN\_harv) but not BasHarv did not perform particularly well relative to models with BasHarv. Delta AICc values for the RipN\_harv models ranged from 7.0 to 12.9 (Table 2). The best model that included RipN\_harv but not BasHarv also included sqrtGlac as a predictor variable (model #32).

### Harvest and Temperature Criteria for Salmonids

Seventeen of 40 streams had at least one seven-day ADM (7DADM) temperature that exceeded 16.0°C, and thus did not meet the Washington State Department of Ecology (DOE) water quality standards for temperature for core salmon rearing and spawning habitat [class AA streams; WAC 173-201A-200(1)(c)]. However, the number of 7DADM temperatures that exceeded 16°C was not well correlated with any harvest patterns. The best predictor was total BasHarv ( $r^2 = 0.16$ ,  $p < 0.01$ ,  $n = 40$ ). For a post hoc analysis, we divided the streams into four categories of total basin harvest: >75, 50-75, 25-50%, and unharvested (<10% harvest). Examination of these categories demonstrates that the probability of a stream exceeding the 7DADM increases as the amount of forest harvest in the basin increases. No unharvested basins had any 7DADM exceedances, while one of six subbasins with 25-50% harvest, nine of eighteen subbasins with 50-75% harvest, and seven of nine subbasins with >75% harvest had 7DADM exceedance (Figure 5). All streams monitored in this study were rated by DOE as class AA or higher.

The maximum temperature observed in any stream during the study was 21.6°C, and only seven streams had a maximum temperature higher than 18°C. Only 11 of 40 streams had 7DADM temperature above 16°C more than 10 times. The maximum seasonal range observed in any stream during the study was 10.2°C and nine streams had a seasonal range >7°C. No stream had an average diurnal fluctuation >4°C, and only seven streams had an average diurnal fluctuation >2°C (Table 1).

### DISCUSSION

The most interesting results from this study are that the amount of recently clear-cut riparian forest immediately upstream of a site was uncorrelated to stream temperature maxima or ranges, and that total

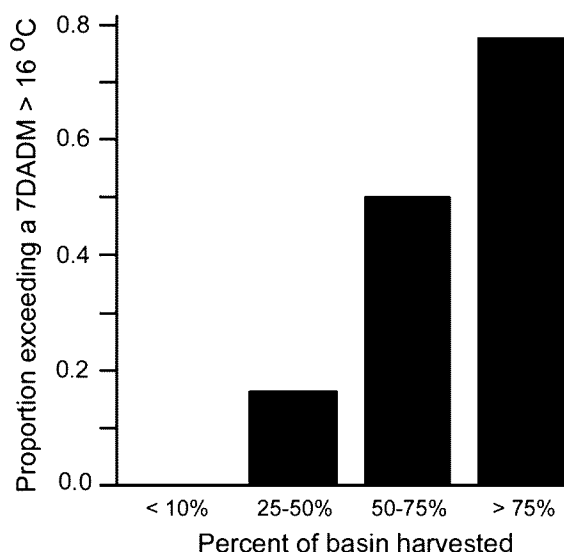


FIGURE 5. The Probability of a Stream Exceeding a Seven-Day Average Daily Maximum (7DADM) Increases as the Amount of Forest Harvest in the Basin Increases. No unharvested basins had any 7DADM exceedances, while one of six subbasins with 25-50% harvest, nine of eighteen subbasins with 50-75% harvest, and seven of nine subbasins with >75% harvest had 7DADM exceedances. The Washington State Department of Ecology water quality standards for temperature for core salmon rearing and spawning habitat [aka class AA streams; WAC 173-201A-200(1)(c)] require that streams do not have a 7DADM in excess of 16°C. All waters monitored in this study were rated by DOE as class AA or higher.

subbasin harvest and total riparian harvest (mostly over the past 40 years) were much better predictors of stream temperature regimes. However, the high degree of correlation between total subbasin harvest and total riparian harvest ( $r = 0.87$ ) means that we were unable to assess whether there were differing effects on stream temperature between these two types of harvest. Anywhere there was extensive harvest within a subbasin, there was also extensive riparian harvest, a result of the limited riparian protection small headwater streams received at the time most of our study sites were logged. Also of related interest was the observation that streams in unharvested subbasins on average ran cooler and fluctuated less than streams in subbasins with harvest activity.

Because direct solar radiation dominates thermal energy inputs to streams, we expected that the amount of shading immediately upstream would be correlated to stream temperature maxima and ranges, as has been demonstrated elsewhere (Brown, 1970; Johnson, 2004). That neither the amount of <20-year-old forest or <10-year-old forest within 600 m upstream of our site was correlated to temperature suggests that the use of broad forest age classes may not be a good surrogate for measures of shade. For example, 61% of the riparian canopy just

upstream of the Spruce Creek site is less than 20-year old, yet the ADM is 10.9°C, one of the coolest streams in our study. As another example, the East Fork Kunamakst Creek has had 100% of the near upstream riparian canopy removed in the past 20 years and it had an ADM of 14.3°C, which was close to the average ADM for harvested subbasins. In contrast, the nearby, similarly sized West Fork Kunamakst Creek has a similar ADM of 14.1°C even though it has had only 18% of the near upstream riparian canopy removed in the past 20 years.

It is also possible, particularly for small streams such as those in our study, that riparian forest growth rates were sufficient to create shade levels for streams similar to older, taller riparian forests in less than 20 years (e.g., see Summers, 1983). For example, Johnson and Jones (2000) examined changes in stream temperature of an uncut, completely clear-cut and patch-cut watershed in western Oregon over several decades. She found that both the patch-cut and clear-cut watersheds had maximum temperature increases of 6–8°C that remained for about 5 years after completion of the treatment. This was followed by a slow decline in maximum temperatures for the next 6–8 years after which maximum temperatures remained approximately equal to those of the uncut watershed. These data suggest, at least for small streams such as those in our study, that stream temperature may not be related to canopy age when the riparian stand is more than 10-year to 15-year old.

That both the total amount of basin harvest and total amount of riparian forest harvest were correlated with ADM and ADR suggests that forest harvest activity is in some way contributing to stream heating other than by exposing the stream surface to direct solar radiation. One possible mechanism is that frequency of slope failures and debris flows increases with increased clear-cutting and roadbuilding (Lyons and Beschta, 1983; Sidle, 1985). Debris flows scour alluvium to create wider, shallower bedrock channels, which are more susceptible to heating (Johnson and Jones, 2000). Also, debris flows remove soils and riparian vegetation adjacent to streams, which increases the canopy opening above streams and delays regeneration of riparian forests. The forest age data used in the analysis did not identify very young riparian stands created by recent debris flows, which could also help explain why we did not see stronger correlations between stream temperatures and the amount of very young riparian forest immediately upstream of sample sites.

Debris flows also affect stream temperatures because they remove large woody debris (LWD) and alluvium, which decreases hyporheic storage and decreases the retention time of water (Holtby, 1988; Johnson, 2004). The exchange of surface waters with

hyporheic ground-water can have an important cooling effect (Poole and Berman, 2001; Johnson, 2004). The extent to which hyporheic flow can cool surface waters depends on the relative volumes of surface flow to hyporheic flow and the difference in temperatures. Hyporheic flow moving through porous alluvium is exposed to a large surface area of cool substrate, which can rapidly conduct heat away from water, so hyporheic flow that has been subsurface for an extended period of time can cool down to substrate temperatures (Poole and Berman, 2001; Johnson, 2004). Since there can be extensive hyporheic exchange in small mountainous streams (Kasahara and Wondzell, 2003), this suggests that debris flow induced loss of alluvium could be a contributing mechanism to the increased stream temperatures we observed in our study.

Increased timber harvest activity in a basin has also been positively correlated to increased peak flows, which should result in wider channels for a given drainage area (Grant and Swanson, 1990; Jones and Grant, 1996). Other studies have also shown positive correlations between timber harvest activity in a basin and channel widths or the widths of canopy openings above streams (Beschta and Taylor, 1988; Dose and Roper, 1994). In their study of a southwestern Oregon watershed, Dose and Roper (1994) found that timber harvest increased channel widths on average by 45%, relative to their widths when no timber harvest had occurred in the basin. These studies suggest that the correlation we observed between total timber harvest and increased stream temperatures might in part be a result of both an increase in the total solar radiation striking streams because of wider canopy openings and an increase in solar radiation absorbed per unit of channel length because of channel widening. For a modeled stream with characteristics similar to the streams we monitored, Bartholow (2000), using Dose and Roper's (1994) data, estimated that a 45% increase in channel width (and canopy opening) could increase stream temperature maxima by about 1.35°C. This would account for a little more than half of the difference in mean ADMs between the harvested (14.5°C) and unharvested (12.1°C) subbasins in our study.

Because of the high degree of correlation between total riparian harvest and total basin harvest, it was not possible to assess the relative importance of the total upstream riparian vs. the total basin harvest on forest stream temperatures. However, our AIC analysis demonstrated that basin harvest was consistently in all the best models predicting ADM temperatures, while total riparian harvest was not (Table 2). The correlation between riparian harvest and total basin harvest exists because few restrictions exist to protect riparian vegetation along the

small streams that constitute most of the stream network in our study area, so most riparian vegetation was harvested concurrent with adjacent upland harvest. Nevertheless, most debris flows are triggered on steep slopes as a result of road construction or timber harvest, so if debris flows are in fact the dominant causal mechanism leading to stream temperature increases, riparian protection further up the stream network would do little to reduce stream temperatures without additional harvest and road construction limits on unstable slopes. At the same time, even in the absence of debris flows, loss of the upstream riparian network can lead to a loss of LWD and a subsequent loss of alluvium, as well as channel widening and shallowing and larger canopy openings downstream. Thus mechanistically, upland forest harvest activities that trigger debris flows and riparian forest harvest may behave similarly in terms of how they affect stream temperature. The major difference is that debris flows are discrete events that instantaneously and dramatically change channel morphology. In contrast, upstream riparian forest removal results in slower, incremental changes in channel morphology that are sometimes only apparent decades after harvest has occurred.

#### Impact of Observed Temperature Increases to Salmonids and Stream-Dependent Amphibians

Temperatures over 16°C, which were observed in many of the streams in our study where timber harvest occurred, exceed the upper limit of optimal temperature for most salmon in western Washington (WSDOE, 2002). In Washington state, the DOE considers streams with one or more 7DADM temperatures above 16°C to be impaired in terms of providing habitat for salmonids [WAC 173-201A-200(1)(c)]. Over half of the streams that had 25% or more of the total watershed forest area harvested (17 out of 33) did not meet Washington DOE's water quality standards for salmonid habitat. Studies have also shown that fluctuations in temperature of the magnitude observed in our study can be harmful to salmon because they increase stress for the fish and inhibit the ability for acclimation to warming temperatures (Hokanson et al., 1977; Coutant, 1999; Torgersen et al., 1999). However, lethal temperatures for salmonids generally occur at temperatures of 21°C or higher, a threshold that was not crossed in the streams in our study. Elevated temperatures of the magnitude we observed might not necessarily be detrimental. When food was abundant, juvenile chinook reached their optimum growth rates at 19°C (Brett et al., 1982). Elevated summer stream temperatures of about 3°C following riparian canopy removal in Carnation Creek, resulted

in larger coho fingerlings and increased overwinter survival (Holtby, 1988). At the same time, elevated spring temperatures resulted in the earlier seaward migration of smolts, which probably resulted in lower smolt-to-adult survival (Holtby, 1988).

The disease susceptibility of salmonids can also go up significantly when exposed to temperatures in the ranges observed in our study. For example, Holt et al. (1978) found that the mortality rate of steelhead, coho, and spring chinook from infection by *Flexibacter columnaris* varied from 4% to 20% among the three species at 12.2°C and increased progressively with increased temperature up to 100% in steelhead and coho salmon at 20.5°C, and to 70% in chinook at that temperature. For all three species, as temperature increased, the minimum time to death also decreased dramatically. For steelhead, coho, and spring chinook, Groberg et al. (1978) found similar relations between temperature and mortality when fish were exposed to the bacteria *Aeromonas salmonicida*, with mortality rates ranging between 18 and 54% at 12.2°C and increasing to 86-96% at 20.5°C.

It is clear there are multiple direct and indirect effects, both positive and negative that stream temperature increases have on salmonids. These effects vary with both species and life history stage, stream temperature itself varies both spatially and temporally, and both the physical habitat of streams and the use of that habitat by different salmonids are highly variable. Given this variability, it is difficult to conclude whether or not the small, but significant (1-4°C) stream temperature increases observed in some streams in this study are having a population-level impact on salmonids. In the absence of additional data, the existing DOE temperature standard is probably the best overall criterion for estimating whether the observed stream temperature increases will affect salmonids.

Stream-dependent amphibians found in our study area are likely to be affected by the temperature increases observed in some of our streams. For example, during embryonic development, tailed frogs prefer temperatures between 4°C and 10°C, and have a maximum tolerance of 18°C (Brown, 1975), while tailed frog tadpoles prefer temperatures around 16°C and few exist in streams with maximum temperatures above 20°C (Hawkins et al., 1988, 1994). In streams below 16°C, adult tailed frogs (*Ascaphus montanus*) showed little movement, while in streams rising above 16°C, adult frog movement increased as they presumably sought out cooler temperatures (Adams and Frissel, 2001).

Other studies have shown a general decline in stream-dependent amphibians following timber harvest, but these did not relate abundances to stream temperature changes (Kelsey, 1994; Richardson and

Neill, 1998). In general, it is difficult to know how much changes in amphibian abundance following timber harvest can be attributed to temperature compared to changes in channel morphology that occur when instream habitat is degraded. Debris flows that scour away the LWD and alluvial habitat in the small headwater streams where stream-dependent amphibians are normally abundant may make these streams inhospitable as much or more than the temperature changes of the magnitude observed in our study.

## CONCLUSIONS

We observed that watersheds with 25-100% of their total area harvested had higher stream temperatures than watersheds with little or no harvest. The magnitude of stream temperature increase was correlated with both the total amount of timber harvest in a watershed and the total amount of riparian forest harvest in a watershed. We did not see any correlation between the amount of recently clear-cut riparian forest immediately upstream of a site and temperature increases. Our study lends support to the hypothesis that forest activities beyond the immediate upstream riparian environment can influence stream temperatures and is consistent with other studies that demonstrate a correlation between the total amount of timber harvest or total riparian harvest in a basin and stream temperature increases (Beschta and Taylor, 1988; Bourque and Pomeroy, 2001). Several causal mechanisms related to timber harvest activity can lead to increased stream temperatures that are sustained for decades or longer. These include widening and shallowing of the channel, widening of the above-channel canopy opening, loss of LWD and alluvium, which reduces hyporheic storage and retention times, and warming of shallow groundwater outside of the riparian zone. Because the streams in our study were in steep mountainous terrain where debris flows are frequently triggered by forest harvest activities, we speculate that total basin harvest or total riparian harvest in our study area may be correlated to debris flow frequency, and that debris flows increase stream temperatures by creating wider, shallower channels with increased canopy openings and reduced hyporheic storage and reduced retention times. We also speculate that even where no debris flows occur, increased basin harvest increases peak flows, which would create wider channels and larger canopy openings above the stream. If increases in stream temperature maxima and ranges are related to changes in debris flow frequency and/or

changes in hydrologic regimes, this suggests that reestablishment of riparian forests alone will not be sufficient to return stream temperature regimes to natural conditions. If hyporheic exchange is an important factor that keeps surface waters cool, as has been demonstrated elsewhere, then to the extent that debris flows and past harvest of headwater riparian forests have removed current and future sources of instream LWD along with the alluvium that is stored behind LWD, recovery of natural temperature regimes in some streams may take centuries.

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